# Morphology and dynamics of the cosmic web

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Chapter 6

# Outlook and future prospects

In this thesis we have introduced a new tool for segmenting the Cosmic Web into its three basic morphological constituents: clusters, filaments and walls. The morphological characterization is performed in scale space. This eliminates the usual restriction of one smoothing scale by taking the maximum morphological response across all scales. This tool, the Multiscale Morphology Filter (MMF) is based on methods developed in the areas of computer visualization and medical imaging. Its multiscale nature makes it suitable for the study of the hierarchical structure of the Universe.

## 6.1 New methods presented in this thesis

- **The Multiscale Morphology Filter**. The main contribution of this thesis is the Multiscale Morphology Filter. We present a novel method for the segmentation of the Cosmic Web into its morphological components. The MMF is used for the first time in an astronomical context and we explore some of its applications.

- **The Delaunay Tessellation Field Interpolator (DTFI)** was developed in order to deal with gaps present in galaxy surveys such as the SDSS. It exploits the geometry of the galaxy distribution in the edges of the gap in order to reconstruct the density field inside the gap. It follows the anisotropies in the galaxy distribution in a self-adaptive way.

- **Filament and wall compression algorithm**, used to *enhance* filaments and walls by compressing them along their spine or plane. The compression algorithm is used to compute the length of filaments, density profiles and to produce a clearer visualization of the Cosmic Web.

- **The FracHOP subhalo finder**. We present a new method for identifying subhaloes located inside larger systems. The FracHOP subhalo finder is based on the well known HOP halo finder. It exploits the topological properties of the smoothed density field in order to identify local maxima embedded inside a larger peak.

## 6.2 Outlook and future prospects

### 6.2.1 The Multiscale Morphology Filter

The Multiscale Morphology Filter, introduced in Chapter 2 is one particular implementation (one we find to be very efficient) of a more general set of multiscale methods taken from the fields of scale-space analysis and feature detection. Many other implementations are possible and perhaps better physically motivated than the one presented here. We performed the feature detection by studying the local properties of the second derivative of the density field. Other measures can be used, such as the gradient of the density field, the gravitational potential, the tidal field, the inertia tensor and even non-physical measures as in the case of the Candy model (Stoica et al., 2005). Some of these measures have already been applied to the identification of features in the matter distribution with some degree of success. The missing link in most cases is the multiscale analysis. It would be very interesting to test the performance of the MMF with other implementations based on the physical measures presented above.

The use of a global "optimal" threshold $\tau$ to separate between "real" and "noisy" structures introduces several complications (see chapter 2, section 2.7). The use of a global threshold assumes that the measures we use to identify morphologies can be compared between all regions of space simultaneously. A locally defined threshold may provide a better segmentation by treating each region of space independently.

The use of the eigenvalues of the Hessian matrix to quantify the significance of a structure is not the only option. Other measures such as the density field and its derivatives, the direction of the eigenvectors of the Hessian matrix or a combination of them may provide a better discrimination. From these, we think that the use of the direction of the eigenvectors is the most promising, especially in the case of filaments and walls where one often finds broken structures or "holes". The local direction of the structures has been successfully applied to the reconstruction of thin bones in Computer Tomography data (Westin, 1997) and may result in a cleaner morphological segmentation. On the other hand, by including more sophisticated algorithms, we risk introducing non-physical artifacts that may limit the applicability (at least in physics) of the morphological segmentation.

The implementation of the MMF we present here is based on the density field computed on a rectangular grid. The intrinsic anisotropic features and multiscale nature of the matter distribution sampled by the particles of galaxies is reconstructed with the use of the DTFE. Other alternatives exist to the use of a rectangular grid,

- The particle distribution can be directly used, avoiding the extra step of computing the density field. By using particles we are not limited by the grid size so we can apply multiscale analysis more efficiently. This may involve the use of more advanced techniques such as working directly with the Delaunay triangulation.

- The use of non-rectangular grids is also possible. In that case it may be necessary to redefine the morphology filters to the new geometry of the pixels. The hexagonal grid has been used in two dimensional images with great success, unfortunately there is no similar pixel geometry for the 3D case. The particular geometry of galaxy surveys may require the use of better sampling geometries such as the *radial sampling*. In this case the local geometry of the pixels can be approximated as being orthogonal in the case of a closely sampled volume.

### 6.2.2 The MMF and the Cosmic Web

In Chapter 3 we study the Cosmic Web in terms of its morphological components. The MMF opens a new door to the study of the Cosmic Web, every result we included can be improved and extended. In particular the study of the properties of filaments and walls. The MMF provides a measure of structureness for each region of space. The raw output of the MMF consists of a single morphology classification per each pixel in the density field. For instance, a filament may consist of a “string” of contiguous pixels classified as filaments by the MMF. We do not have information on the extent of the structure, its density profile, topology, branching properties, etc. One must introduce many post-processing tools that allows us to compute relevant physical quantities from the raw output of the MMF. The post-processing tools we present here can be easily improved, in particular the definition of the length of filaments and eventually the two-dimensional area of walls. The branching properties of filaments is also interesting in the context of fractal measures of the matter distribution.

The MMF can be used to compute the fractal properties of the *compressed filamentary network*, giving emphasis to filaments as a network of interconnected elements. With the MMF we can also study the evolution of each morphological component and trace them back to their initial conditions. This may provide an excellent test to the Cosmic Web Theory (Bond et al., 1996) by studying the proto-structures and the tidal field from which they emerge.

### 6.2.3 Properties of dark matter haloes in the Cosmic Web

In Chapter 4 we present a study of the properties of haloes in relation to their morphological environment. The most logical extension is a follow-up study including a better mass resolution, dissipative gas and semi-analytical galaxy formation. Higher mass resolution will solve some of our present limitations in computing the properties of low mass haloes. The gas component will make it easier to compare our results with observations, especially the contrived spin alignment.

We presented a preliminary study of the infall of matter in haloes located inside filaments and walls. This study requires a more detailed treatment, taking into account not only the infall of matter, but the tidal shear induced by the surrounding matter distribution. This will help clarify the different contributions to the shape and spin of dark matter haloes from the anisotropic infall defined by the large scale structure and the (closely related) external tidal shear.

With the use of semi-analytical models it will be possible to study properties of galaxies such as Hubble type, color, star formation rate, etc. as function of their morphological environment. These results can be directly compared to similar analysis performed from redshift galaxy catalogues such as the SDSS.

### 6.2.4 The Cosmic Web in the SDSS

In Chapter 5 we present a study of the spin alignment of spiral galaxies located inside filaments. The galaxies were obtained from the Sloan Digital Sky Survey, data release 5. We found a significant dependence of alignment with color and luminosity. More blue luminous galaxies tend to be more strongly aligned. We identified a sample of $\sim 30$ spiral galaxies that present a significant alignment with their host filament. This sample reflects a general (weak) trend of the spin vector of spiral galaxies to be parallel with their host filament. This result is the opposite we found in computer simulations for high mass haloes although the number of galaxies we use is too small to draw firm conclusions.

The study presented here is restricted to the spin alignment of spiral galaxies. Many other properties are also interesting and physically relevant in the context of galaxy formation and evolution. Some well known properties and relations can be studied by including the morphological environment in which the galaxy is located. Just to name a few we have the morphology-density relation, the color-magnitude diagram, the ratio of interacting and warped galaxies in different environments, etc.

The effect of redshift distortions, specially the fingers of God must be studied in more detail. The finger of God compression algorithm affects the identification of filaments located along the line of sight. In order to identify and correct them we only rely on the spatial information. A perhaps better approach will involve the use of properties of galaxies such as color and even morphology in addition to their position.

We did not attempt to identify walls. Their detection poses a major challenge, walls are delineated by low-mass haloes which may host dwarf galaxies. Also, walls have a very low surface density. Perhaps a better approach is to identify walls by the structures that delineate them such as the filament-void network.

## 6.3 Final conclusions

We have presented a novel method that allows us to define environment in terms of its morphology. The Multiscale Morphology Filter provides a complete framework to identify clusters, filaments and walls in a self-consistent way. It deals in a natural way with the three key aspects of the Cosmic Web:

- **Hierarchical clustering**. The scale-space analysis in which the MMF is based is perfectly suited to describe the multiscale nature of the Cosmic Web.
- **Anisotropic features** are identified with the use of three separate morphology filters used in a strict sequential order.
- **The cellular nature of the Cosmic web** is implicitly assumed in the identification of filaments and walls. This marks a difference between the MMF and other feature detections techniques; the MMF is specially designed to exploit the unique connectivity properties of the Cosmic Web.

By segmenting the Cosmic Web into its basic morphological components we are able to study the properties of each morphology independently. Properties of filaments, walls as well as their content can be studied and compared to theoretical predictions. This is a crucial advantage of the MMF since many theoretical studies are based on idealized cases. This often makes it very difficult to test theory against observations without a proper morphological characterization.

We hope that the MMF presented here (or other perhaps better implementations) will open the path towards a better understanding of the complex relation between the elements of the Cosmic Web and their close relation to the formation of galaxies and their evolution.